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(71) Applicant: FUJITSU LIMITED
Kawasaki-shi, Kanagawa 211 (JP)

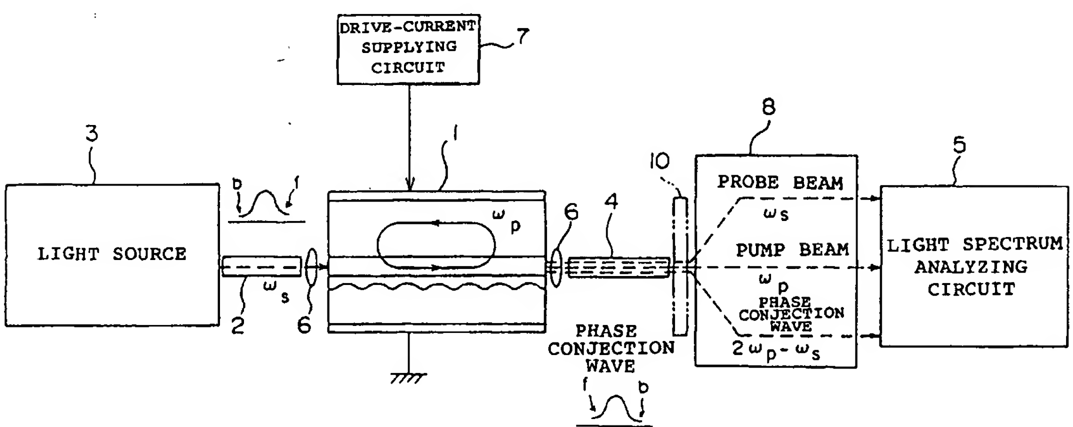
(72) Inventor: Kuwatsuka, Haruhiko
Nakahara-ku, Kawasaki-shi, Kanagawa 211 (JP)

(74) Representative: Melnick, Geoffrey Lionel et al
Haseltine Lake & Co.,
Imperial House,
15-19 Kingsway
London WC2B 6UD (GB)

(54) Phase conjugate wave generating device, wavelength converting method, optical dispersion compensation method and multi-wavelength light generating device

(57) There is provided a device comprising a distributed feedback semiconductor laser (1) having a $\lambda/4$ phase shift diffraction grating (13) and antireflection films (22X) coated on a light input end and a light output end to transmit phase conjugate waves a probe beam light source for injecting the probe beam into the light input end of the distributed feedback semiconductor laser (1), a current supplying means (7) for supplying electric current to the distributed feedback semiconductor laser (1) to oscillate a pump beams and a lens system (6) for extracting phase conjugate wave which is output from the light output end of the distributed feedback semiconductor laser (1) by injecting the probe beam into the distributed feedback semiconductor laser (1) which is oscillating the pump beam.

FIG.2



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Description

The present invention relates to a phase conjugate wave generating device, a wavelength converting method, an optical dispersion compensating method, and a multi-wavelength light generating device. More particularly, the present invention relates to a device for generating a phase conjugate wave by using nondegenerative four-wave mixing (ND-FWM), a method of converting wavelength by using NDFWM, a method of compensating for optical dispersion with the use of NDFWM, and a device for generating plural lights having different wavelengths.

Various investigations with phase conjugate wave have been carried out once it was found that using phase conjugate waves could compensate for dispersion in optical fibers used in optical communication. Thus applications of phase conjugate wave to a wavelength converting mechanism in feature wavelength multiplication communication and the like may be expected. As shown in FIG.1, in wavelength multiplication communication without phase conjugate waves, not only must as many semiconductor lasers 101 to 107 be prepared as the number of different wavelengths used but also output light beams from these semiconductor lasers 101 to 107 must be superposed by an optical coupler 120 via optical fibers 111 to 117. Thus the system tends to increase in size and becomes complicated as the number of wavelengths increases.

As methods of generating phase conjugate waves, for purposes of example, a method of a employing the optical nonlinearly of an optical fiber, a method of employing a traveling-wave type semiconductor laser amplifier, a method of employing a semiconductor laser wavelength which is fixed by injection of the light, etc. has been proposed.

The method of generating phase conjugate wave by making use of the traveling-wave type semiconductor laser amplifier has been recited in A. Mecozzi et al., IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL.31, NO.4, April 1995, pp.689-699, [1].

In this method, as shown in FIG.6 of [1], a pump (excitation) beam and a probe beam (also called a "signal beam") are coupled by a directional coupler, then the pump beam and the probe beam coupled is input into the traveling-wave type semiconductor laser amplifier via a lens system and an optical isolator , and then phase conjugate waves are extracted from the traveling-wave type semiconductor laser amplifier.

The light output from a color center laser (CCL) is fed as the pump beam to the directional coupler via an optical isolator (OI), a Babinet-Soleil compensator, and a lens system. The light output from an external-cavity laser diode (ECLD) is fed as the probe beam to the directional coupler via the optical isolator, a $\lambda/2$ plate, and a $\lambda/4$ plate.

The method of generating phase conjugate waves with the use of the semiconductor laser in lieu of the semiconductor laser amplifier has been recited in Patrick P. Iannone et al., IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL.31, NO.7, July 1995, pp.1285-1291, [2]

In this method, a device having similar mechanism to that given in [1] has been employed except for the use of the semiconductor laser. The semiconductor laser is formed to oscillate the light having the same wavelength as that of the pump beam injected externally.

These two methods have in common that both the pump beam and the probe beam are input into one end of the semiconductor laser amplifier or the semiconductor laser and that the phase conjugate wave of the probe beam is extracted from the other end of the semiconductor laser amplifier or the semiconductor laser.

In contrast, the method of inputting externally the probe beam into the semiconductor laser oscillating the pump beam and outputting phase conjugate waves of the probe beam incident end has been set forth in S. Murata et al., Appl. Phys. Lett. 58(14), 8 April 1991, pp.1458-1460, [3].

However, according to the methods recited in the above citations [1] and [2], since three optical devices such as a light source for generating the probe beam, a light source for generating the pump beam, and a semiconductor laser amplifier or semiconductor laser for generating phase conjugate wavesis needed, a mechanism for coupling these components with each other becomes complicated correspondingly. In particular, an optical coupler for efficiently coupling the probe beam with the excitation beam with required.

Moreover, in the method set forth in the citation [3], a Fabry-Perot mode resides in the semiconductor laser because there is a need for a reflection film having a high reflection factor on the light non-output end of the semiconductor laser, for outputting phase conjugate waves. Accordingly, as described in citation [3], the wavelength of the phase conjugate wave is limited inevitably to the wavelength that resonates with the Fabry-Perot mode.

It is thus desirable to provide a phase conjugate wave generating device for allowing a phase conjugate wave generating mechanism to be more simple and to generate phase conjugate wavesnot depending upon a Fabry-Perot mode, a wavelength converting method for converting wavelength by generating such phase conjugate waves, a method for compensating for optical dispersion with the use of such phase conjugate waves, and a multi-wavelength light generating device for generating a plurality of light beams having different wavelengths.

According to an aspect of the present invention, since the DFB semiconductor laser is used as the semiconductor device to generate phase conjugate wave and a single mode light beam obtained by oscillating the DFB semiconductor laser is used as the pump beam, a mechanism for coupling the pump beam with the probe beam can be neglected to thereby simplify the structure of the phase conjugate wave generating device. In addition, there is no necessity to

consider attenuation of intensity of the pump beam due to the optical fiber, and intensity of the phase conjugate wave as the output light beam can be enhanced by the stronger pump beam.

Though the DFB semiconductor laser has a single oscillation mode, wavelength can be varied freely. For varying wavelength, for instance, distribution of the electric current supplied to the semiconductor laser may be altered in magnitude by splitting the electrode on one side of the DFB semiconductor laser into a plurality of electrodes. Accordingly, it is possible to alter the wavelength of the pump beam with the use of the DFB semiconductor laser. As a result, the wavelength of the phase conjugate wave can be varied freely.

Since the phase conjugate wave (light beam) generated by the DFB semiconductor laser is output with the probe beam and the pump beam, the filter may be arranged on the output end side of the DFB semiconductor laser if only the phase conjugate wave light beam needs to be extracted.

Since the waveform of the phase conjugate wave light beam appears as a reversal waveform of the probe beam if the DFB semiconductor laser is used, the DFB semiconductor laser can be used to compensate for dispersion in the optical fiber.

According to another aspect of the present invention, the loop-like optical path is provided such that the input end of one DFB semiconductor laser having different oscillation wavelength is connected to the output end of the other DFB semiconductor laser and then the input end of the other DFB semiconductor laser is connected to the output end of one DFB semiconductor laser, and the light beam in the optical path is extracted to the outside by the directional branch coupler or the like.

Since a plurality of light beams having different wavelengths and passing through in the loop-like optical path may serve as the probe beam,a plurality of phase conjugate waves having different wavelengths may be generated by each DFB semiconductor laser. Therefore, since the multi-wavelength light generating device may consist of as few as two DFB semiconductor lasers, the optical fiber, and the light outputting device to miniaturize the size, the device can be miniaturized and time and labor required for assembling can be reduced because of a reduction in the number of connecting points between the optical parts and the optical device.

Also, insertion of the etalon in the loop-like optical path allows intensity of the light beam to be amplified. Besides, if the isolator is inserted in the loop-like optical path, a component of the light beam proceeding in the reverse direction can be decreased.

Since the interval between wavelengths of the light beam can be changed by varying the wavelength of the DFB semiconductor laser, the wavelength of the output light beam can be readily adjusted.

For a better understanding of the invention, and to show how the same may be carried into effect, reference will be made, purely by way of example, to the accompanying drawings, in which:-

FIG.1 is a view showing an example of a type of conventional device for entering plural lights having different wavelengths into an optical fiber;

FIG.2 is a view showing a type of phase conjugate wave generating device according to an embodiment of the present invention;

FIG.3A is a perspective view, partially cut away, showing a DFB semiconductor laser for use in the phase conjugate wave generating device according to the embodiment of the present invention;

FIG.3B is a sectional view showing the DFB semiconductor laser taken along a line I-I in FIG.3A;

FIG.4 is a graph showing an example of spectrum derived from the phase conjugate wave generating device according to the embodiment of the present invention;

FIG.5 is a view showing an example of a configuration of a multi-wavelength light generating device to which the phase conjugate wave generating device according to the embodiment of the present invention is applied;

FIG.6 is a view showing an example of optical spectra having different frequencies generated by the phase conjugate wave generating device according to the embodiment of the present invention; and

FIG.7 is a side view showing an example of temperature control of the DFB semiconductor laser used in the phase conjugate wave generating device according to the embodiment of the present invention.

There will be described various embodiments of the present invention with reference to the accompanying drawings. It is to be noted that the same or similar reference numerals are applied to the same or similar parts and elements throughout the drawings, and the description of the same or similar parts and elements will be omitted or simplified.

FIG.2 is a view showing a configuration of a phase conjugate wave generating device according to an embodiment of the present invention with the use of NDFWM.

In FIG.2, a variable wavelength light source 3 is connected to one end (light incident end) of the DFB semiconductor laser 1 via a first optical fiber 2. A light spectrum analyzing circuit 5 is connected to the other end (light emitting end) of the DFB semiconductor laser 1 via a second optical fiber 4 and a light receiving device 8.

The DFB semiconductor laser 1 has a structure shown in FIGS.3A and 3B, for example.

In FIG.3A, an n-InGaAsP guide layer 12 is formed on an upper surface of an n-InP substrate 11. A corrugated

diffraction grating 13 with a film thickness which varies periodically in the light passing direction is formed on a junction surface between the guide layer 12 and the substrate 11. As shown in FIG.3B, the diffraction grating 13 has in the central portion 13c a phase shift type in which the period is shifted by $\lambda/4$ (where λ is wavelength of light in the waveguide).

An undoped multiple quantum well (MQW) active layer 14 is formed on the guide layer 12, and a p-InGaAsP buffer layer 15 and a p-InP layer 16 are formed on the active layer 14. The MQW active layer 14 is formed such that five layers of 7 nm thick $In_{x'}Ga_{1-x'}As$(x'=0.532) well layers and five layers of 10 nm thick $Ga_xIn_{1-x}As_yP_{1-y}$(x=0.283, y=0.611) barrier layers are alternatively stacked.

The p-InP layer 16 to an upper portion of the n-InP substrate 11 are patterned to assume a convex portion in section. A plan shape of the convex portion is a stripe shape extending in the light passing direction. A p-InP layer 17 and a n-InP layer 18 are formed in sequence on the n-InP substrate 11 on both sides of the stripe-like convex portion. A p-InGaAsP layer 19 is formed on the uppermost layer, i.e., the p-InP layer 16 and the n-InP layer 18.

An n side electrode 20 is formed on a lower surface of the n-InP substrate 11. In addition, three split p side electrodes 21a, 21b, 21c are formed on the p-InGaAsP layer 19.

An energy band gap of n-InP is larger than the active layer 14. And, InP around the active layer 14 is a cladding layer.

Reflection-free films 22X are coated on both end surfaces of the DFB semiconductor laser 1 respectively to transmit at least phase conjugate wave. Merely by way of example, a resonator length of the DFB semiconductor laser 1 is 900 μm, a length of the p side electrode 21b formed in the center area is about 580 μm, lengths of the p-side electrodes 21a, 21c formed on the side areas are 160 μm.

In FIG.2, a reference 6 denotes a focusing lens, and a reference 7 denotes a driving current supplying circuit for supplying a drive current to the DFB semiconductor laser 1.

Subsequently, an operation of the above phase conjugate wave generating device will be explained.

At first, by supplying a drive current to the n side electrode 20 of the DFB semiconductor laser 1 from the p side electrodes 21a, 21b, 21c via the MQW active layer 14, a light with wavelength of 1549 nm can be continuously oscillated from one end of the MQW active layer 14 at an output of 40 mW. In this case, electric currents with the same magnitude such as 400 mA are supplied to respective p side electrodes 21a, 21b, 21c.

Since the light beam oscillated from the DFB semiconductor laser 1 has a single laser mode and a narrow line width in the wavelength band, oscillating light has a stable wavelength. Therefore, the light beam of angular frequency ω_p oscillated by the DFB semiconductor laser 1 may be used as the pump beam (excitation beam).

Next, the probe beam of wavelength 1574 nm is output from a variable wavelength light source 3. Then, the probe beam is input into an input end of the DFB semiconductor laser 1 via a first optical fiber 4 and a focusing lens 6. At this time, spectrum of the light beam output from the other end of the DFB semiconductor laser 1 has been examined by making use of a light spectrum analyzing circuit 5. The result of such examination is shown in FIG.4.

In FIG.4, in addition to a spectrum peak of the pump beam at a wavelength of 1549 nm and a spectrum peak of the probe beam at a wavelength of 1574 nm, another spectrum peak exists at a wavelength of 1524 nm. As a result, it could be seen that a third beam other than the pump beam and the probe beam can be output from the DFB semiconductor laser 1.

Let ω_s be the angular frequency of the probe beam and ω_c is the angular frequency of the third beam, it has been found that the third light beam is phase conjugate wave since the following equation (1) can be deduced from the experimental results in FIG.4.

$$\omega_c = 2\omega_p - \omega_s \tag{1}$$

Among angular frequency ω of the light beam, frequency ν of the light beam, and wavelength λ of the light beam, relationships $\omega=2\pi\nu$, $\lambda=v/\nu$ can be satisfied. Where v is light velocity.

As stated earlier, if the pump beam is generated in the DFB semiconductor laser 1, a mechanism for coupling the probe beam with the pump beam can be omitted, thus result in simplification of a configuration of the phase conjugate wave generating device. Hence, miniaturization of an optical communication device into which such device is incorporated can be accomplished.

Without regards to attenuation in intensity of the pump beam through the optical fiber, intensity of the phase conjugate wave serving as the output light beam can be enhanced by stronger pump beam rather than that in the conventional device since the pump beam is generated in the DFB semiconductor laser 1. This is because intensity of phase conjugate wave varies directly as square of intensity of the pump beam.

Next, distribution of electric current supplied to the p side electrodes 21a, 21b, 21c of the DFB semiconductor laser 1 will be explained.

Such event has been set forth in Y. KOTAKI et al., OFC '90, THURSDAY MORNING, 159 that, if magnitude of

electric currents Ia, Ib, Ic supplied to three p side electrodes 21a, 21b, 21c is set differently, a single oscillation mode (wavelength) of the DFB semiconductor laser 1 is shifted.

For instance, by increasing the electric current Ib injected into the central p side electrode 21b while keeping the electric currents Ia, Ic injected into the p side electrodes 21a, 21c formed near both ends of the DFB semiconductor laser 1 constant, shift of oscillation wavelength towards the longer wavelength side would occur. The electric currents supplied to respective p side electrodes 21a, 21b, 21c can be adjusted by a drive-current supplying circuit 7.

Thus, if the DFB semiconductor laser 1 having a plurality of p side electrodes 21a, 21b, 21c shown in FIG.3B and the reflection-free films 22X on its both ends is used, wavelength of phase conjugate wave can be altered freely by varying wavelength of the pump beam.

As discussed above, with the use of the above phase conjugate wave generating device, wavelength conversion can be attained in the wavelength multiplication communication.

Meanwhile, the phase conjugate wave output from the above DFB semiconductor laser 1 exists axially symmetrically to the probe beam with respect to the pump beam. For this reason, as shown in FIG.2, in case the probe beam is pulse-modulated to have a longer wavelength λ_f at a front portion of the pulse and a shorter wavelength λ_b at a rear portion of the pulse, waveform of the phase conjugate wave is deformed such that wavelength is shortened like λ_b at a front portion of the pulse of the probe beam and is lengthened like λ_f at a rear portion thereof.

By putting this phenomenon into practice, with passing through the first optical fiber 2 having a length of 50 km, for example, the pulse-like probe beam (signal light beam) is spread because of dispersion in the optical fiber and then input into the DFB semiconductor laser 1, so that the phase conjugate wave also assumes a spread waveform. In this case, wavelength is lengthened at the front portion of the pulse of the probe beam rather than the rear portion thereof.

However, waveform of the phase conjugate wave appears as a reversal of waveform of the probe beam in size of wavelength at the front and rear portions. Therefore, if the second optical fiber 4 is 50 km in length, for example, pulse waveform of the light beam is compressed as the light beam proceeds in the second optical fiber 4, so that the pulse waveform is deformed desirably to have the original narrow pulse width. This is because longer wavelength components of the pulse tends to travel more quickly in the optical fiber rather than shorter wavelength components of the pulse.

Subsequently, explanation will be made of a light generating device for generating a light having different frequencies with the use of a plurality of above phase conjugate wave generating devices.

FIG.5 shows a multi-wavelength light generating device which generates plural lights at predetermined frequency interval by using two DFB semiconductor lasers each having a different oscillation wavelength.

A first DFB semiconductor laser 22 and a second DFB semiconductor laser 23 are formed to have substantially identical configurations to that shown in FIGS.3A and 3B, but such DFB semiconductor lasers have different oscillation wavelengths since they are formed to have either different pitches of diffraction grating 13 or different compositions of well layers and barrier layers in the MQW layers 14. Where, let ν_1 be the frequency of oscillation beam of the first DFB semiconductor laser 22 and ν_2 be the frequency of oscillation beam of the second DFB semiconductor laser 23.

An input end 22a of the first DFB semiconductor laser 22 is connected to an output end 23b of the second DFB semiconductor laser 23 via a first optical fiber 24. An input end 23a of the second DFB semiconductor laser 23 is connected to an output end 22b of the first DFB semiconductor laser 22 via a second optical fiber 25. Thus, the first DFB semiconductor laser 22 and the second DFB semiconductor laser 23 are in the same condition as they are connected in series to a loop-like optical path.

Further, in the optical loop in FIG.5, an isolator 26 is connected to the first optical fiber 24 in serial so as to advance the light beam clockwise in the first optical fiber 24, for instance. The isolator 26 is provided to prevent return reflection along the optical path.

Furthermore, a Fabry-Perot etalons 27 with frequency (ν_1-ν_2) is connected to a second optical fiber 25 in series. Such a configuration may be considered as the Fabry-Perot etalons 27 that, for instance, two flat glasses are provided in parallel and a reflection layer is formed between inner surfaces of these parallel flat glasses.

Moreover, a directional branch coupler 28 having almost X-shape optical paths is connected to the second optical fiber 25. Parts of the second optical fiber 25 are connected in series to optical paths on one side of the directional branch coupler 28, while optical paths on the other side of the directional branch coupler 28 are connected to the external devices via a third optical fiber 29.

A first drive-current supplying circuit 30 is connected to the first DFB semiconductor laser 22 and a second drive-current supplying circuit 31 is connected to the second DFB semiconductor laser 23.

The multi-wavelength light may be emitted from the multi-wavelength light generating device composed as above as follows.

First, by supplying electric currents from the first drive-current supplying circuit 30 and the second drive-current supplying circuit 31 to the first DFB semiconductor laser 22 and the second DFB semiconductor laser 23 respectively, a first light beam of frequency ν_1 may be oscillated from the first DFB semiconductor laser 22 and a second light beam of frequency ν_2 may be oscillated from the second DFB semiconductor laser 23.

The first light beam and the second light beam emitted from the first DFB semiconductor laser 22 and the second

DFB semiconductor laser 23 respectively proceed clockwise in the first optical fiber 24 and the second optical fiber 25. Then, the first light beam of frequency ν_1 is input into an input end of the second DFB semiconductor laser 23 while the second light beam of frequency ν_2 is input into an input end of the first DFB semiconductor laser 22.

Since the frequency ν is expressed by $\omega/2\pi$, the light beam of frequency given by relationship of the above equation (1) in the following is present in the loop-like optical path.

At first, a third light beam of frequency ν_3 given by the following equation (2) is output from the first DFB semiconductor laser 22 to which the second light beam of frequency ν_2 is input.

$$\nu_3 = 2\nu_1 - \nu_2 = \nu_1 + (\nu_1 - \nu_2) \quad (2)$$

Similarly, a fourth light beam of frequency ν_4 given by the next equation (3) is output from the second DFB semiconductor laser 23 to which the first light beam of frequency ν_1 is input.

$$\nu_4 = 2\nu_2 - \nu_1 = \nu_2 - (\nu_1 - \nu_2) \quad (3)$$

Further, when the fourth light beam is input into the first DFB semiconductor laser 22 via the optical fiber, it may serve as the probe beam and then a fifth light beam of frequency ν_5 given by the equation (4) as well as the first and third light beams is output from an output end of the second DFB semiconductor laser 23.

$$\begin{aligned}\nu_5 &= 2\nu_1 - \nu_4 = 2\nu_1 - (2\nu_2 - \nu_1)\\ &= (2\nu_1 - \nu_2) + (\nu_1 - \nu_2)\\ &= \nu_3 + (\nu_1 - \nu_2)\end{aligned} \quad (4)$$

Furthermore, when the third light beam is input into the second DFB semiconductor laser 23 via the optical fiber, it may serve as the probe beam and then a sixth light beam of frequency ν_6 given by the equation (5) as well as the second and fourth light beams is output from the output end of the second DFB semiconductor laser 23.

$$\begin{aligned}\nu_6 &= 2\nu_2 - \nu_3 = 2\nu_2 - (2\nu_1 - \nu_2)\\ &= (2\nu_2 - \nu_1) - (\nu_1 - \nu_2)\\ &= \nu_4 + (\nu_1 - \nu_2)\end{aligned} \quad (5)$$

As evident from the above, plural light beams having frequencies at a $(\nu_1 - \nu_2)$ interval with respect to frequency ν_1 of the pump beam for the device may be output from the first DFB semiconductor laser 22 whereas plural light beams having frequencies at a $-(\nu_1 - \nu_2)$ interval with respect to frequency ν_2 of the pump beam for the device may be output from the second DFB semiconductor laser 23.

The same relations as given by the equations (2) to (5) may be satisfied with respect to $1/\lambda$ of respective light beams.

It is assumed, by way of example, that oscillation wavelength and oscillation light output of the first DFB semiconductor laser 22 are 1550 nm and 40 mW respectively and oscillation wavelength and oscillation light output of the second DFB semiconductor laser 23 are 1552 nm and 40 mW respectively, then eight different wavelength light beams having output of about 1mW can be emitted at an approximate 2 nm wavelength interval.

Such wavelength interval may be varied by changing oscillation wavelength (pump beam) of the first or second DFB semiconductor laser 22 or 23, for example.

Also, in order to vary oscillation wavelength of the DFB semiconductor laser, as shown in FIG.3B, the electrode formed on one side of the DFB semiconductor laser may be split into plural electrodes and then electric currents supplied to these plural electrodes may be adjusted. Instead of splitting the electrode of the DFB semiconductor laser, as shown in FIG.7, a Peltier device 30 and a thermistor 31 may be brought into contact with the first or second DFB semiconductor laser 22 or 23, then temperature of to the first or second DFB semiconductor laser 22 or 23 may be detected by the thermistor 31 to input a temperature controlling circuit 32, and then temperature of the first and second DFB semiconductor lasers 22, 23 may be kept at a desired value while controlling electric current supplied to the Peltier

device 30 by the temperature controlling circuit 32 in accordance with the detected temperature. This is because oscillation frequency of the DFB semiconductor laser varies within a predetermined range according to change in temperature.

In this manner, if the output and input ends of the first and second DFB semiconductor lasers 22, 23 is placed in the loop-like optical path and then phase conjugate wave light beam generated by the first and second DFB semiconductor lasers 22, 23 may be used, as shown in FIG.6, plural light beams can be generated at a predetermined interval. Since plural light beams having different frequencies are spread in the directional coupler 28 until the third optical fiber 29, part of these light beams can be extracted to an external device via the third optical fiber 29.

When passing through the loop-like first and second optical fibers 24, 25, anti-clockwise traveling of plural-frequency light beam can be prevented from by the isolator 26. Intensity of the light beam in first and second optical fibers 24, 25 is reduced as frequency deviates from ν_1 or ν_2. However, if the light beam is passed through the first and second DFB semiconductor lasers 22, 23, it is amplified because of their semiconductor gain medium and further amplification operation is accelerated with the aid of the Fabry-Perot etalon having resonance energy interval of ν_1-ν_2. Therefore, actually available frequency range can be widened.

As mentioned above, if the DFB semiconductor laser is employed to generate phase conjugate wave, the light beam having plural frequencies can be generated with the use of at least two DFB semiconductor lasers. Therefore, not only the multi-wavelength light generating device can be miniaturized but also connection of the optical fiber in the device can be significantly reduced to thus improve operation efficiency. It is of course that three DFB semiconductor lasers or more may be used in the loop-like optical path.

Although the DFB semiconductor laser 1 has been formed as a InP/InGaAsP layer structure in the above embodiment, other InP/InAlGaAs layer structure may be used. In addition, materials which is matched with the GaAs substrate may be used.

For practical use, in the phase conjugate wave generating device, light emitting diode, semiconductor laser, etc. may be used in place of the variable wavelength light source 3, and a filter 10 for transmitting only phase conjugate wave light beam may also be attached on the outside of the output end of the DFB semiconductor laser 1. The filter 10 may be arranged between the DFB semiconductor laser 1 and the lens 6, or between the lens 6 and the optical fiber 4.

As has been described above, according to an aspect of the present invention, since the DFB semiconductor laser is used as the semiconductor device to generate phase conjugate wave and a single mode light beam obtained by oscillating the DFB semiconductor laser is used as the pump beam, a mechanism for coupling the probe beam with the pump beam can be neglected to thereby simplify the structure of the phase conjugate wave generating device. In addition, there is no necessity to consider attenuation of intensity of the pump beam due to the optical fiber, and intensity of the phase conjugate wave as the output light beam can be enhances by the stronger pump beam.

Though the DFB semiconductor laser has a single oscillation mode, wavelength can be varied freely. For instance, distribution of the electric current supplied to the semiconductor laser can be altered in magnitude by splitting the electrode on one side of the DFB semiconductor laser into plural electrodes. As a result, wavelength of the phase conjugate wave can be varied freely.

Since the phase conjugate wave (light beam) generated by the DFB semiconductor laser is output together with the probe beam and the pump beam, only the phase conjugate wave light beam can be extracted by arranging the filter on the output end side of the DFB semiconductor laser.

Since waveform of the phase conjugate wave light beam appears as a reversal waveform of the probe beam if the DFB semiconductor laser is used, the DFB semiconductor laser can be used to compensate for dispersion in the optical fiber.

According to another aspect of the present invention, the loop-like optical path is provided such that the input end of one DFB semiconductor laser having different oscillation wavelength is connected to the output end of the other DFB semiconductor laser and then the input end of the other DFB semiconductor laser is connected to the output end of one DFB semiconductor laser, and the light beam passing through in the loop-like optical path is input into respective DFB semiconductor lasers as the probe beam so as to generate plural phase conjugate waves having different wavelengths. Hence, the multi-wavelength light generating device may consists of at least two DFB semiconductor lasers, the optical fiber, and the light outputting device to miniaturize the size. Moreover, reduction in the number of connecting points of the optical fiber can yield less time and labor required for assembling.

Also, insertion of the etalon in the loop-like optical path allows intensity of the light beam to be amplified. Besides, if the isolator is inserted in the loop-like optical path, component of the light beam proceeding in the reverse direction can be decreased.

Since interval between wavelengths of the light beam can be changed by varying wavelength of the DFB semiconductor laser, wavelength of the output light beam can be readily adjusted.

Various modifications will become possible for those skilled in the art after receiving the teachings of the present disclosure without departing from the scope of the appended claims.

Claims

1. A phase conjugate wave generating device comprising:

   a distributed feedback semiconductor laser (1) having an optical input end and an optical output end, reflection-free films (22X),capable of transmitting phase conjugate waves,being formed on respective ends, and a grating structure (13) enabling single mode oscillation;
   a probe beam generating light source (3) for injecting a probe beam into said optical input end of said distributed feedback semiconductor laser (1);
   means (7) for supplying electric current to said distributed feedback semiconductor laser (1) to oscillate a pump beam; and
   means (8) for detecting said phase conjugate waves output from said optical output end of said distributed feedback semiconductor laser (1) by injecting said probe beam into said distributed feedback semiconductor laser (1) which is for oscillating said pump beam.

2. A phase conjugate wave generating device according to claim 1, wherein said distributed feedback semiconductor laser (1) has a wavelength variable structure.

3. A phase conjugate wave generating device according to claim 2, wherein said wavelength variable structure includes a one-side electrode (21a-21c) which is divided into a plurality of portions within said distributed feedback semiconductor laser (1), and said electric current supplying means (7) for adjusting electric current to be supplied to said electrode (21a-21c).

4. A phase conjugate wave generating device according to claim 1, 2 or 3, wherein a filter (10), for transmitting said phase conjugate waves only,is arranged on the outside of said optical output end of said distributed feedback semiconductor laser (1).

5. A phase conjugate wave generating device according to claim 1,2,3 or 4 wherein said distributed feedback semiconductor laser (1) includes a $\lambda/4$ phase shift diffraction grating (13c) on its inside.

6. A wavelength converting method comprising the steps of:

   oscillating a distributed feedback semiconductor laser (1) which has reflection-free films (22) for transmitting phase conjugate waves on an optical input end and an optical output end, by supplying electric current thereto; and
   converting wavelength by irradiating said optical input end of said distributed feedback semiconductor laser (1), whilst in an oscillation state,with a probe beam, so as to emit phase conjugate wave light from said optical output end.

7. An optical dispersion compensating method comprising the steps of:

   oscillating a distributed feedback semiconductor laser (1) which has a grating structure (13) enabling single mode oscillation, and reflection-free films (22X) for transmitting phase conjugate waves on an optical input end and an optical output end,by supplying electric current to it;
   inputting a probe beam which is passed through a first optical fiber (2),and a signal waveform which is distorted by dispersion in said first optical fiber (2) into said optical input end of said distributed feedback semiconductor laser; and
   outputting phase conjugate wave light, which is output from said distributed feedback semiconductor laser (1) by inputting said probe beam, from a second optical fiber (4) having a length identical to that of said first optical fiber (1) after said probe beam has been restored to its original waveform by compensating said dispersion by being passed through said second optical fiber (4).

8. A multi-wavelength light generating device comprising:

   at least a first and a second distributed feedback semiconductor laser (22,23), which have different oscillation wavelengths;
   a loop optical path (24,25) for connecting in series an input end of the first distributed feedback semiconductor laser (22) to an output end of the second distributed feedback semiconductor laser (23);

an electric current source (30,31) for supplying electric current to at least said first and said second distributed feedback semiconductor lasers (22,23); and
an optical output means (28) for extracting a part of the light beam in said loop optical path (24,25).

9. A multi-wavelength light generating device according to claim 8, wherein an etalon (27) is inserted into a part of said loop optical path (24,25), and the resonance energy interval of said etalon (27) is selected to be identical to the difference in energy of the light beams oscillated by at least said first and said second distributed feedback semiconductor lasers (22,23).

10. A multi-wavelength light generating device according to claim 8 or claim 9, further comprising an isolator (26) inserted into part of said optical path.

11. A multi-wavelength light generating device according to claim 8, 9, or 10, said optical output means (28) being made up of a directional branch coupler.

12. A multi-wavelength light generating device according to claim 8, 9, 10 or 11 wherein oscillation wavelength alternating/controlling means is provided to at least said first and said second distributed feedback semiconductor lasers (22,23).

13. A multi-wavelength light generating device according to claim 12, wherein said oscillation wavelength alternating-controlling means is a means for controlling a quantity of electric current for every divided electrode (21a-21c) of said distributed feedback semiconductor lasers (22,23).

14. A multi-wavelength light generating device according to claim 12, wherein said oscillation wavelength alternating/controlling means (31,32) is a means for controlling the temperature of said distributed feedback semiconductor lasers (22,23).

FIG.1 (Prior Art)

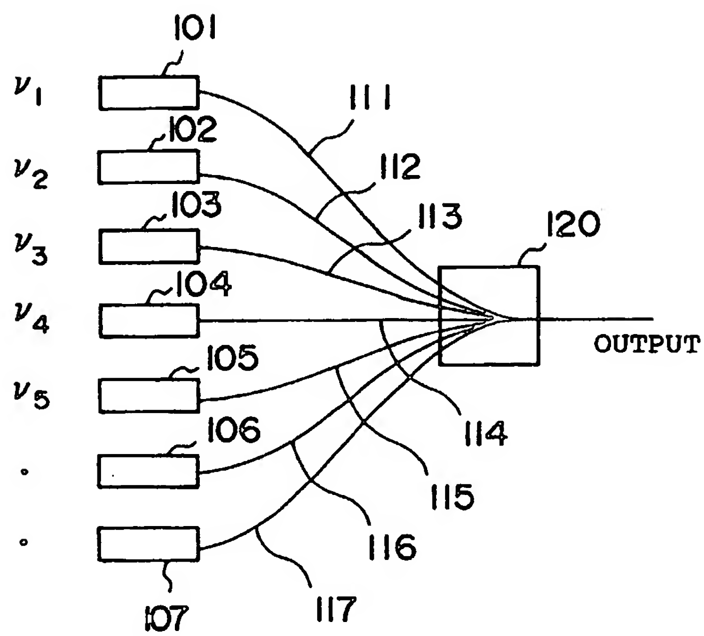


FIG.2

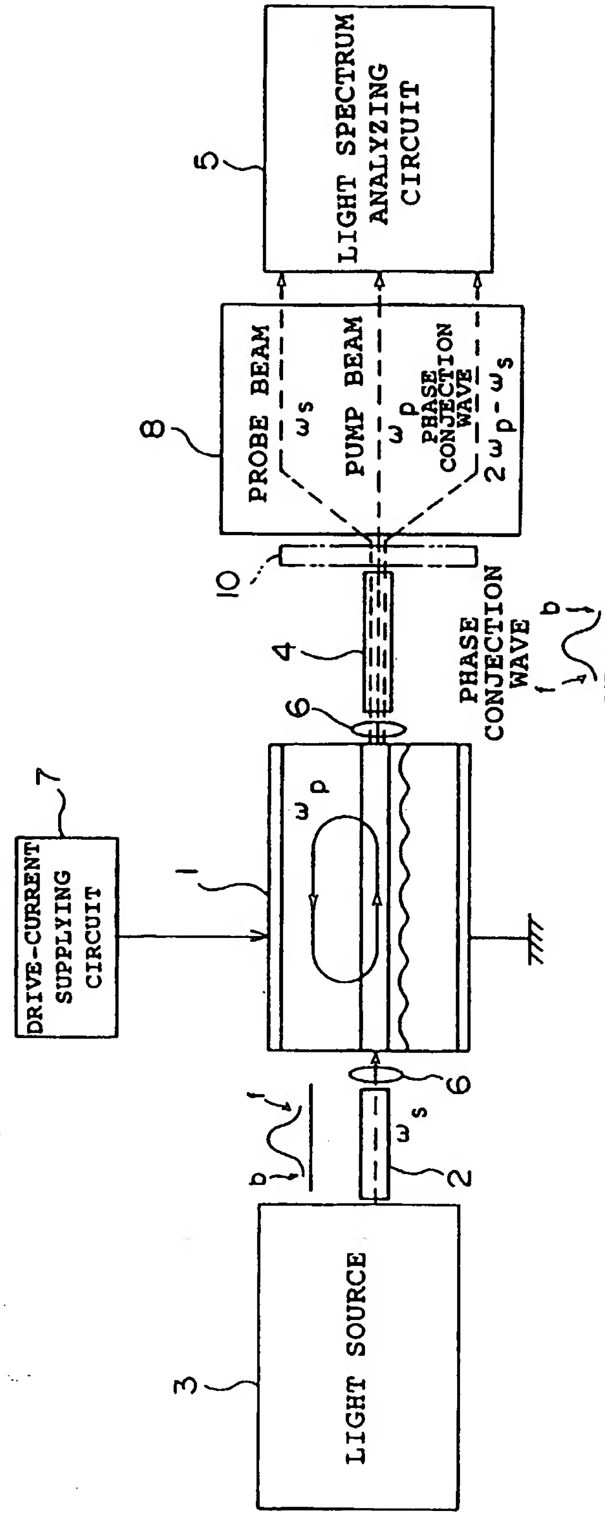

LIGHT SPECTRUM ANALYZING CIRCUIT
5
PROBE BEAM
ω_s
PUMP BEAM
ω_p
PHASE CONJECTION WAVE
$2\omega_p-\omega_s$
8
10
4
PHASE CONJECTION WAVE
6
ω_p
7
DRIVE-CURRENT SUPPLYING CIRCUIT
1
6
ω_s
2
LIGHT SOURCE
3

FIG.3A

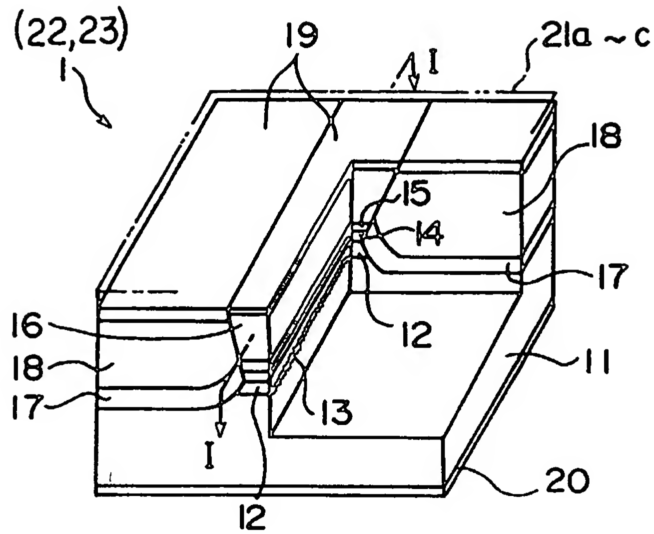

(22,23)
1
19
I
21a ~ c
18
15
14
17
16
18
17
12
11
13
I
20
12

FIG.3B

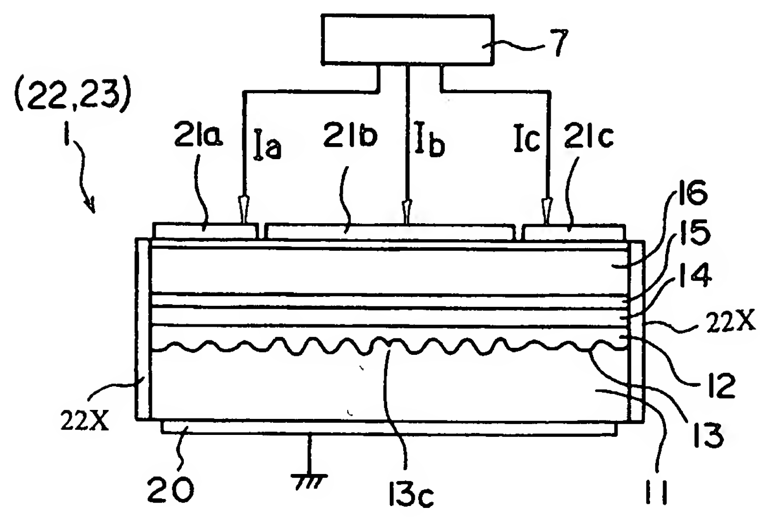

7
(22,23)
1
21a
Ia
21b
Ib
Ic
21c
16
15
14
22X
12
13
22X
20
13c
11

FIG.4

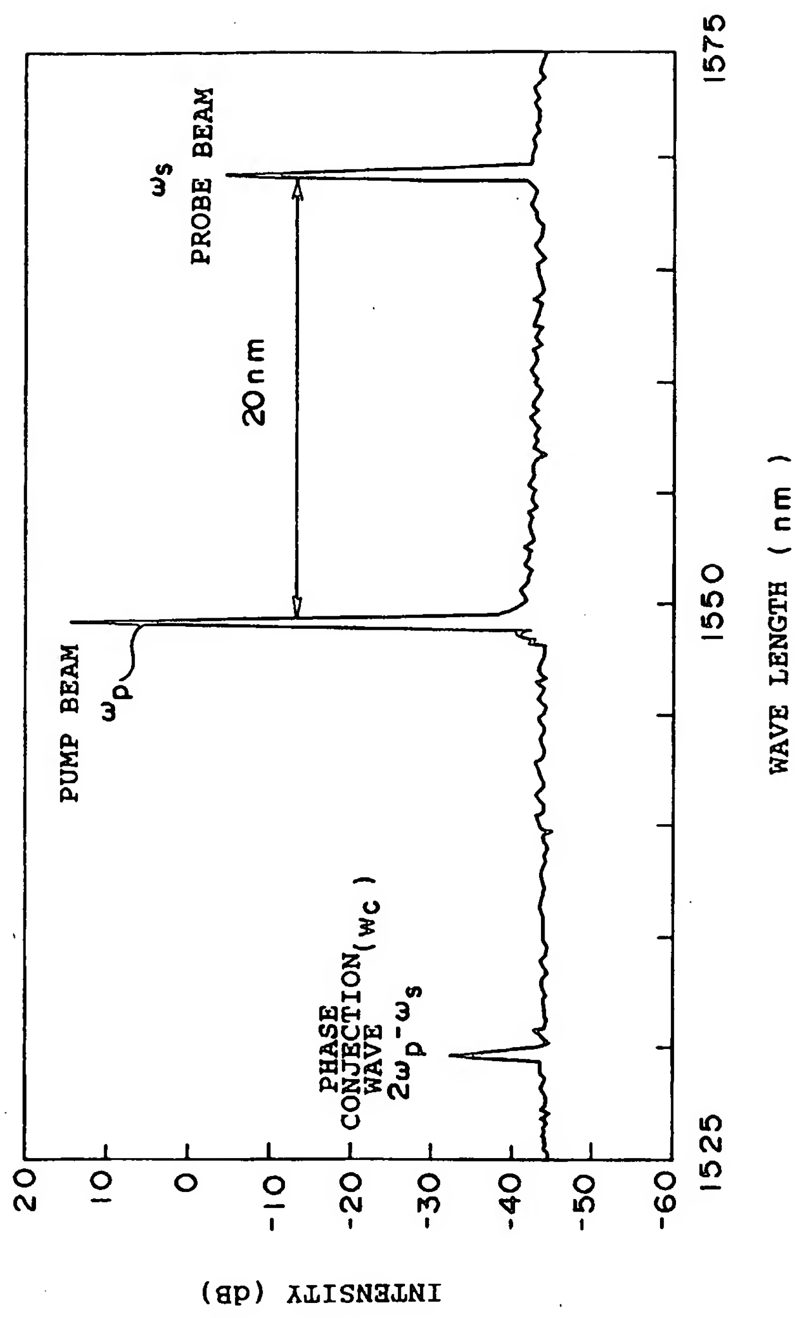
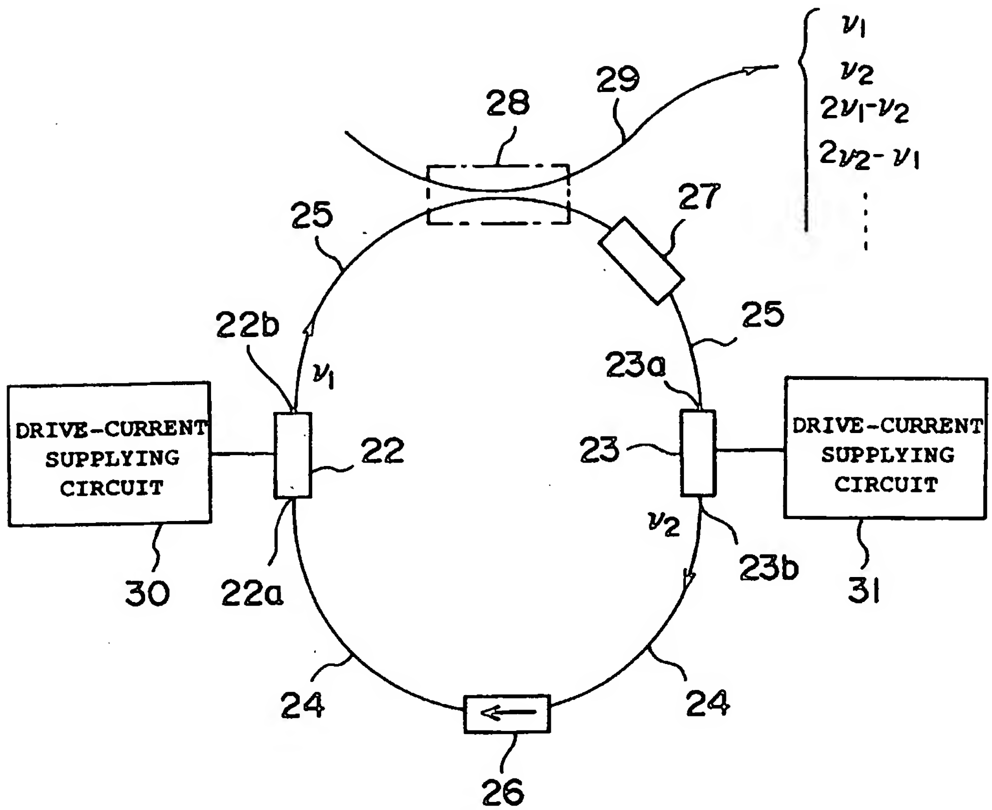

PUMP BEAM
ω_p
ω_s
PROBE BEAM
20nm
PHASE CONJECTION WAVE
$2\omega_p - \omega_s$
(w_c)
INTENSITY (dB)
WAVE LENGTH (nm)
20
10
0
-10
-20
-30
-40
-50
-60
1525
1550
1575

FIG.5



ν_1
ν_2
$2\nu_1-\nu_2$
$2\nu_2-\nu_1$
29
28
27
25
25
22b
ν_1
23a
DRIVE-CURRENT SUPPLYING CIRCUIT
22
23
DRIVE-CURRENT SUPPLYING CIRCUIT
ν_2
30
22a
23b
31
24
24
26

FIG.6

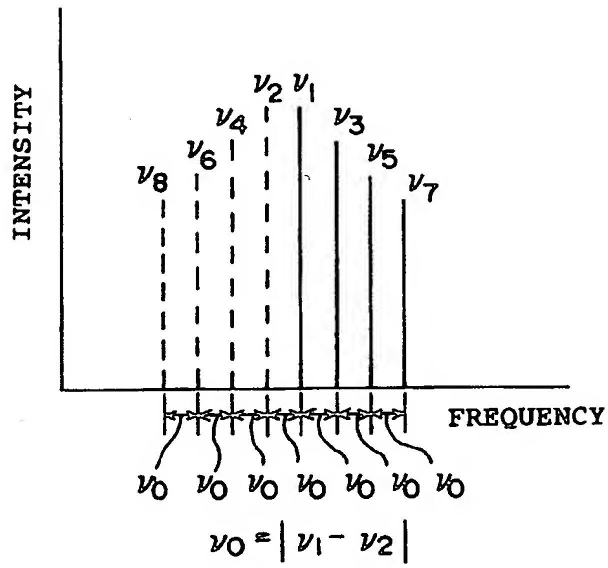
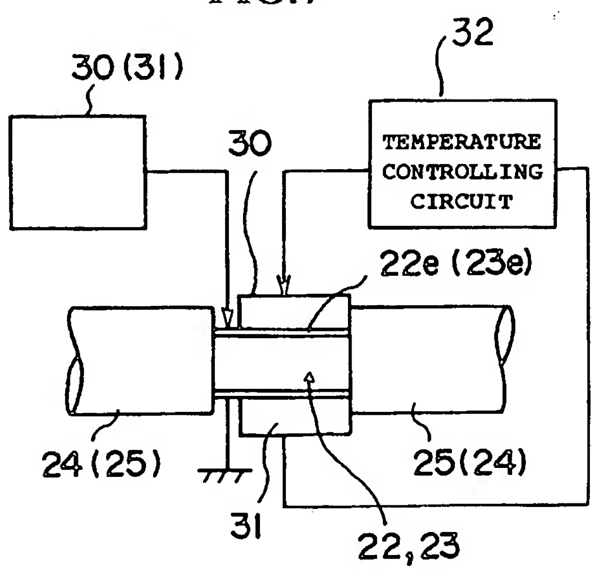

INTENSITY
ν_2 ν_1
ν_4
ν_3
ν_6
ν_5
ν_8
ν_7
FREQUENCY
ν_0 ν_0 ν_0 ν_0 ν_0 ν_0 ν_0
$\nu_0 = |\nu_1 - \nu_2|$

FIG.7


32
30(31)
30
TEMPERATURE
CONTROLLING
CIRCUIT
22e (23e)
24(25)
25(24)
31
22,23

(19) Europäisches Patentamt
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(71) Applicant: FUJITSU LIMITED
Kawasaki-shi, Kanagawa 211-8588 (JP)

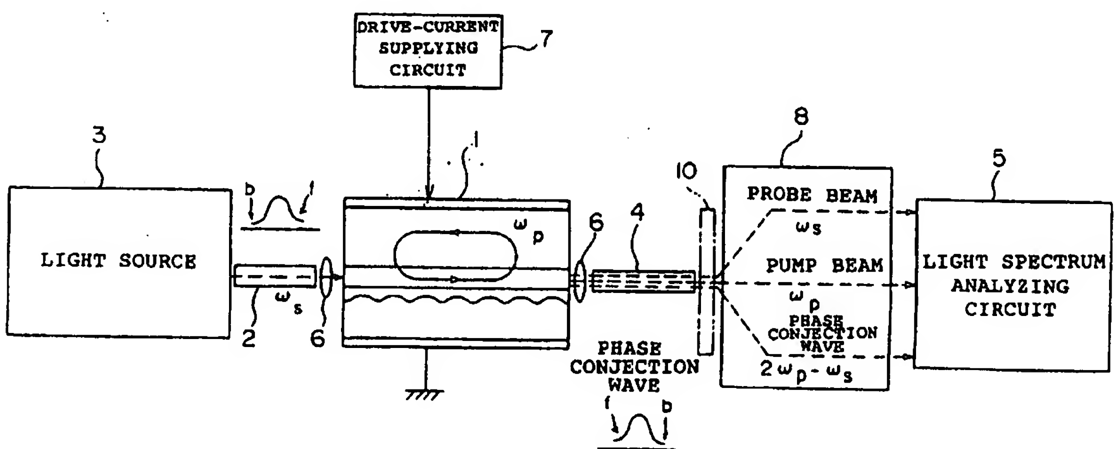
(72) Inventor: Kuwatsuka, Haruhiko
Nakahara-ku, Kawasaki-shi, Kanagawa 211 (JP)

(74) Representative: Melnick, Geoffrey Lionel et al
Haseltine Lake & Co.,
Imperial House,
15-19 Kingsway
London WC2B 6UD (GB)

(54) Phase conjugate wave generating device, wavelength converting method, optical dispersion compensation method and multi-wavelength light generating device

(57) There is provided a device comprising a distributed feedback semiconductor laser (1) having a λ/4 phase shift diffraction grating (13) and antireflection films (22X) coated on a light input end and a light output end to transmit phase conjugate waves a probe beam light source for injecting the probe beam into the light input end of the distributed feedback semiconductor laser (1), a current supplying means (7) for supplying electric current to the distributed feedback semiconductor laser (1) to oscillate a pump beams and a lens system (6) for extracting phase conjugate wave which is output from the light output end of the distributed feedback semiconductor laser (1) by injecting the probe beam into the distributed feedback semiconductor laser (1) which is oscillating the pump beam.

FIG.2



EP 0 774 810 A3

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EUROPEAN SEARCH REPORT

Application Number
EP 96 30 8248

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
X Y A	MECOZZI A ET AL: "NEARLY DEGENERATE FOUR-WAVE MIXING IN DISTRIBUTED FEEDBACK SEMICONDUCTOR LASERS OPERATING ABOVE THRESHOLD" IEEE JOURNAL OF QUANTUM ELECTRONICS, vol. 29, no. 6, June 1993, pages 1477-1487, XP002025888 * page 1477 - page 1478; figure 1 *	1,2,6 7 3-5	H01S3/25 G02F1/35 H04B10/18
X	RONGQING HUI ET AL: "OPTICAL FREQUENCY CONVERSION USING NEARLY DEGENERATE FOUR-WAVE MIXING IN A DISTRIBUTED-FEEDBACK SEMICONDUCTOR LASER: THEORY AND EXPERIMENT" JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 11, no. 12, 1 December 1993, pages 2026-2032, XP000422663 * the whole document *	1,6	
Y	WO 95 03653 A (BRITISH TELECOMM ;TATHAM MARTIN CHRISTOPHER (GB); SHERLOCK GERARD) 2 February 1995 * the whole document *	7	TECHNICAL FIELDS SEARCHED (Int.Cl.6) H01S G02F H04B
A	PATENT ABSTRACTS OF JAPAN vol. 013, no. 352 (E-801), 8 August 1989 & JP 01 111389 A (NEC CORP), 28 April 1989, * abstract *	1-5	
D,A	MURATA S ET AL: "OBSERVATION OF HIGHLY NONDEGENERATE FOUR-WAVE MIXING (>1 THZ) IN AN INGAASP MULTIPLE QUANTUM WELL LASER" APPLIED PHYSICS LETTERS, vol. 58, no. 14, 8 April 1991, pages 1458-1460, XP000209753 * the whole document * -/--	1,6	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	11 June 1998	Claessen, L

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EUROPEAN SEARCH REPORT

Application Number
EP 96 30 8248

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	ELECTRONICS LETTERS., vol. 21, no. 3, January 1985, ENAGE GB, XP002067750 * figure 1 *	8,9	
A	EP 0 385 697 A (BRITISH TELECOMM) 5 September 1990 * the whole document *	8	
A	EP 0 643 460 A (FRANCE TELECOM) 15 March 1995 * abstract; figure 3 *	8	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)

The present search report has been drawn up for all claims

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